International Journal of Sciences and Techniques of Automatic control & computer engineering
IJ-STA, Volume 1, N° 2, December 2007, pp. 167–180.

Modified Direct Torque Control of Permanent Magnet Synchronous Motor Drives

Mohamed Kadjoudj[1], Soufiane Taibi[1], Noureddine Golea[2], Hachemi Benbouzid[3],
[1] Electrical Engineering Departement, Batna university, Algeria,
kadjoudj_m@yahoo.fr

[2]Electrical Engineering Departement, Batna university, Algeria,
nour_golea@yahoo.fr
[3] IUT Brest, Department GEII, university western Brittany, French.
m.benbouzid@ieee.org

Abstract. *The industrial application areas of the direct torque contro (DTC) scheme have been increased due to several features, namely, elimination of the mandatory rotor position sensor, less computation time, fast torque response androbustness against motor parameter variations. In addition, the stator resistance is the only parameter, which should be known and no reference frame transformation is required. The implementation of DTC in PMSM drives is described and the switching tables specific for an interior PMSM are derived. The conventional eight voltage-vector switching table, which is namely used in the DTC of induction motor, does not seem to regulate the torque and stator flux in PMSM well when the motor operates at low speed. Modelling and simulation studies have both revealed that a six voltage-vector switching table is more appropriate for PMSM drive at low speed. Different switching algorithms using hysteresis and non-hysteresis controllers are proposed and the effectiveness of the strategies are discussed. In addition, a modified method is propoed which introduces dither signal injection so that the flux and torque ripples are reduced.The sources of difficulties, namely, the variation of stator phase resistance and the offsets in measurement of current and DC-link voltage are also described and analysed.*

Keywords. DTC, PMSM, Hysteresis and non-hysteresis controllers, switching tables.

1. Introduction

Permanent magnet synchronous motor drives (PMSM) offers many advantages over the induction motor, such as overall officiency, effective use of reluctance torque, smaller losses and compact motor size. In recent years many studies have been developedto find out different solutions for the PMSM drive control having the features of quick and precise torque response, and reduction of the complexity of field oriented control algorithms. The DTC technique has been recognised as viable and robuste solution to achieve these requirements.

In the existing literature, many algorithms have been suggested for the DTC control. The eight voltage-vector switching scheme seems to be suitable only for high speed operation of the motor while at low speed the six voltage-vector switching

This paper was recommended for publication in revised form by the editor Staff.
Edition: CPU of Tunis, Tunisia, ISSN: 1737-7749

scheme, avoiding the two zero voltage-vectors, seems to be appropriate for the permanent magnet synchronous motor drive [1] [2]. The voltage vector strategy using switching table is widely researched and commercialized, because it is very simple in concept and very easy to be implemented. The stator fluxes linkage are calculated from voltage and current models PMSM drive. The DTC is increasingly drawing interest because of,

- Simplicity of its structure.
- Elimination of the current controllers.
- Inherent delays.
- Elimination of rotor position sensor.

The switching frequency can not practically increased when the hysteresus band width is sufficiently reduced because of delay time in estimating current and flux. In order to overcome this problem, a modified DTC method is proposed introducing a dither signal by superposing a high frequency and small amplitude triangular or sine wave on the torque and flux errors as it is shown in figure 1. According to the modelling results, the stator flux and torque ripples were reduced to 25% compared to those of conventional scheme and this enables the controiller to raise the switching frequency regardkess of the delay time and also makes acoustically silent drive possible.

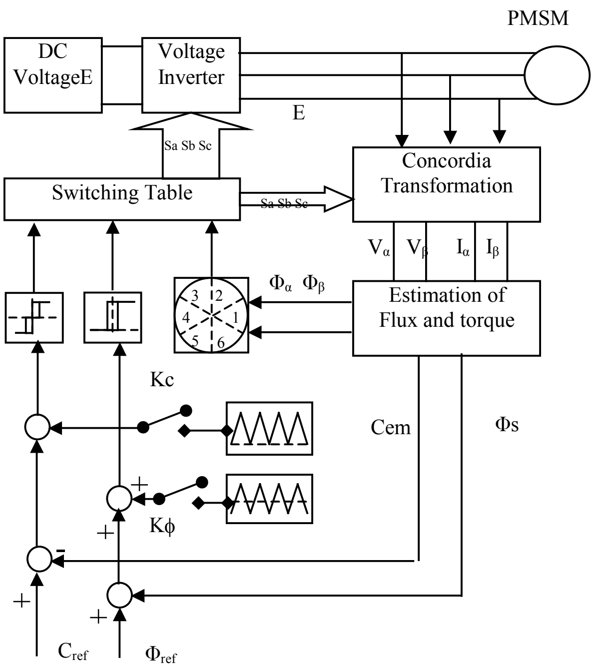

Figure 1. Modified DTC control

Two direct torque control schemes for PMSM drive with injection of dither signal and with non hysteresis controllers are proposed in this paper, which features in low torque and flux ripples and almost fixed switching frequency. The torque and flux ripples have been significantly reduced if compared with those of the basic DTC.

This paper investigates the problem of the offset error in estimating stator flux linkage and torque for DTC controlled PMSM drives. The PMSM model suffers from several problems. Firstly, the measured signals of the inverter DC-link voltage and motor phase currents suffer from the offsets which in turn result in inaccurate of the stator flux linkage and torque. Secondly, the variation of the stator resistance due to change in temperature and stator input frequency also contribute in the error significantly especially at low speed when the voltage drop may become significant compared to the amplitude of the voltage input. This error manifests itself in producing large errors in the computation of the stator flux estimation [5][6].

2. Machine Equation.

The motor considered in this paper is an interior PMSM which consists of a three phase stator windings and a PM rotor. The voltage equations in a synchronous reference frame can be derived as follows [3][4],

$$V_d = R_s.I_d.+\frac{d\phi_d}{dt} - \omega_r.\phi_q \quad (1)$$

$$V_q = R_s.I_q.+\frac{d\phi_q}{dt} + \omega_r.\phi_d \quad (2)$$

Where the direct and quadrature axis flux linkages are,

$$\phi_d = L_d.I_d.+\phi_f \quad (3)$$

$$\phi_q = L_q.I_q \quad (4)$$

The electromagnetic torque of the motor can be evaluated as follows,

$$C = \frac{3}{2}n_p.\{\phi_f.I_q + (L_d - L_q).I_d.I_q\} \quad (5)$$

The motor dynamics can be simply described by the equation (6).

$$\frac{J}{n_p}\frac{d\omega_r}{dt} + \frac{f}{n_p}.\omega_r = C_{em} - C_{st} \quad (6)$$

By using the concept of the field orientation, it can be assumed that the d-axis current is controlled to be zero. Thus, the PMSM has the best dynamic performance and also operates in the most efficient state. Under this assumption, the contribution of the second term of the electric torque equation becomes effectively negligible and the reduced dynamic model of the PMSM is given by the following equations [5][6].

$$\frac{dI_q}{dt} = \frac{1}{L_q}.V_q - \frac{R_s}{L_q}.I_q - \frac{\phi_f}{L_q}.\omega_r \tag{7}$$

$$\frac{J}{n_p}\frac{d\omega_r}{dt} = K_T.I_q - \frac{f}{n_p}.\omega_r - C_{st} \tag{8}$$

$$\frac{d\theta}{dt} = \omega_r \tag{9}$$

3. Voltage switching tables.

The torque and flux hysteresis controllers select the appropriate voltage vectors described in figure 2. Tables 1 and 2 indicate the six and eight voltage vectors switching strategies, in each region C and ϕ are increasing or decreasing functions of time. From table 2, it is clear that when the torque is increasing or decreasing, the flux linkage can be increased or decreased by selecting alternatively one of the six non zero voltage vectors and one of the two zero voltage vectors as it is shown in figure 3.

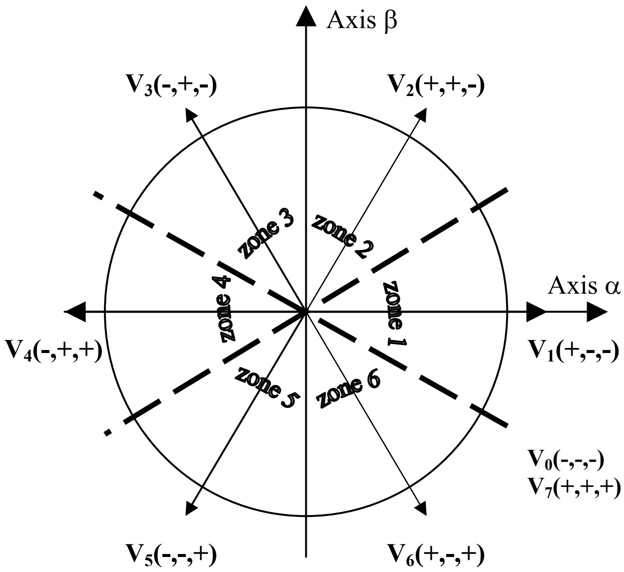

Figure 2. Sectors and voltage vectors.

From table 1, the torque and flux are increased or decreased by selecting only the six non zero voltage vectors. The torque is changed by reversing the movement of the stator flux vector at each state of the hysteresis controller output [7][8].

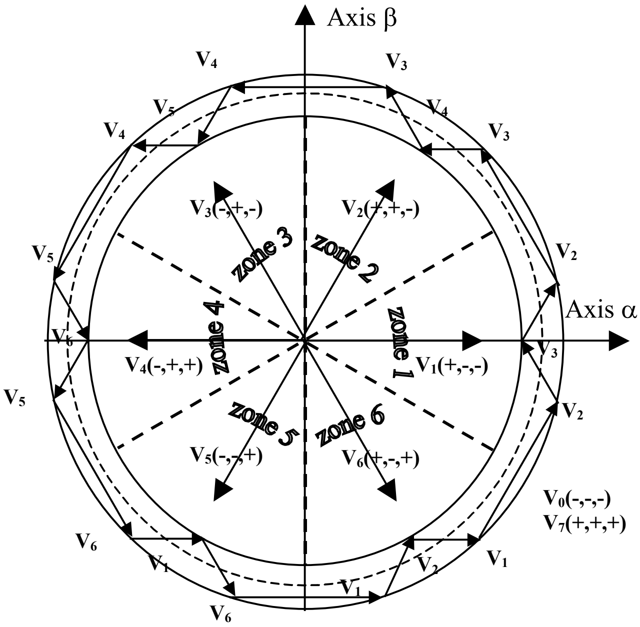

Figure 3. Control of stator flux linkage with selected stator voltage vectors.

The use of the six voltage vectors switching table implies that the stator flux linkage is always kept in motion, making it to go forward and backward in order to regulate the torque loop. For controlling the amplitude of stator flux and therefore for changing the torque, zero voltage vectors V_7 and V_0 are not used in PMSM drives. In tables 1 and 2, R_ϕ and R_C are the outputs of the hysteresis controllers. Z=1,…6 represent the regions numbers for the stator flux linkage positions [9] [10].

		Z=1	Z=2	Z=3	Z=4	Z=5	Z=6
$R_\phi=1$ ($\phi\uparrow$)	$R_c=1$ ($C\uparrow$)	V_2	V_3	V_4	V_5	V_6	V_1
	$R_c=0$ ($C\downarrow$)	V_6	V_1	V_2	V_3	V_4	V_5
$R_\phi=0$ ($\phi\downarrow$)	$R_c=1$ ($C\uparrow$)	V_3	V_4	V_5	V_6	V_1	V_2
	$R_c=0$ ($C\downarrow$)	V_5	V_6	V_1	V_2	V_3	V_4

Table 1. The six voltage vectors switching table

		Z=1	Z=2	Z=3	Z=4	Z=5	Z=6
$R_\phi=1$ ($\phi\uparrow$)	$R_c=1$($C\uparrow$)	V_2	V_3	V_4	V_5	V_6	V_1
	$R_c=0$($C\downarrow$)	V_7	V_0	V_7	V_0	V_7	V_0
$R_\phi=0$ ($\phi\downarrow$)	$R_c=1$($C\uparrow$)	V_3	V_4	V_5	V_6	V_1	V_2
	$R_c=0$($C\downarrow$)	V_0	V_7	V_0	V_7	V_0	V_7

Table 2. The eight classic voltage vectors switching table

To study the performance of the DTC control, the simulation of the system was conducted using Matlab programming environment. Figure 4 shows that the motor can follow the command torque very well. However, relatively high torque ripples are observed [11][12].

The PMSM was simulated under the DTC drive system at high and low speed. Figure 5 revealed loss of control over torque and stator flux when the zero voltage algorithm is used, these could not be attributed to factors such offsets in the measurements of motor terminal quantities and the variation of stator resistance which are known sources of problems in DTC. It is seen however that the ripples in torque and flux characteristics are considerably lower when the eight voltage vectors in table 2 are used. This implies that table 2 is more appropriate for high speed operations.

As mentioned earlier, the torque is proportional to the angle δ, which must be changed quickly. Unlike the asynchronous motor where change of slip frequency brought about by applying zero voltage vectors, the angle δ in the case of PMSM is determined also by the position of the rotor flux linkage which is non zero at all times.

To control torque at low speed, quick change of δ can be obtained by avoiding the zero voltage vectors and by applying vectors which move the stator flux relative to rotor flux as quickly as possible. At high speed, this may not be necessary where the rotor move sufficiently to produce the required change in torque [13]. The conventional eight voltage vector switching table is normally used in the DTC of induction motors and does not seem to regulate the torque and stator flux in PMSM drive well when the motor operates at low speed [14].

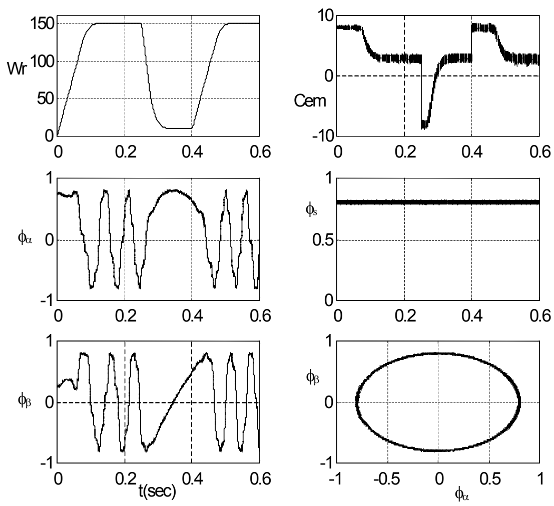

Figure 4. DTC without zero voltage vectors.

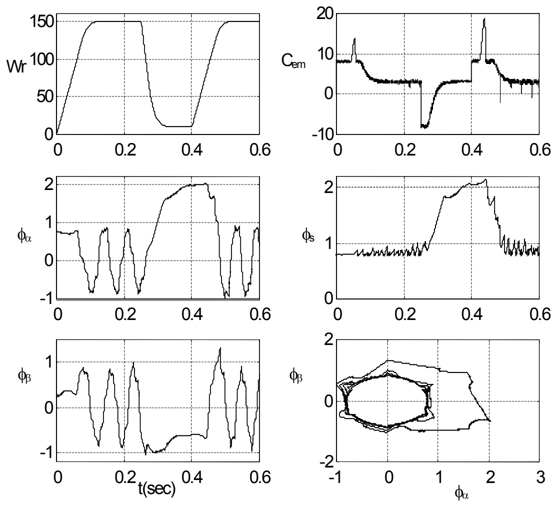

Figure 5. DTC with zero voltage vectors

The switching frequency variation characteristic of the flux hysteresis controller is different from that of torque hysteresis controller. The switching frequency has a maximum value in a medium speed range. For the flux controller, the switching frequency is proportional to the motor speed. This phenomenon makes flux and torque hysteresis controllers to have different contributions to the total switching frequency.

4. DTC with non-hysteresis controllers.

Different switching algorithms using non-hysteresis controllers are proposed. The difference between the actual stator flux and its reference value and the difference between the motor torque and its reference value are controlled over a hysteresis cycle with defined levels which dictate the inverter switching pattern. In this technique, there is no hysteresis controller and history of the flux and torque errors do not play any role in the switching of the inverter. This non-hysteresis controller technique can be classified based on the number of the error levels. Advantages of the later technique are,

- Simplicity of the flux and torque controllers compared with the hysteresis controllers.
- Lower switching frequency.
- Limitation of the amplitude of the current harmonics.

For the multi bands torque and flux controllers, the control algorithm can be summarized as follows,

Rule A	$e_c > \Delta C$	then	$R_c=0$
	$0 \le e_c \le \Delta C$	then	$R_c=1$
	$-\Delta C_1 \le e_c < 0$	then	$R_c=2$
	$-\Delta C_2 \le e_c < -\Delta C_1$	then	$R_c=3$
	$e_c < -\Delta C_2$	then	$R_c=4$
Rule B	$e_\phi > \Delta\phi$	then	$R_\phi=0$
	$0 \le e_\phi \le \Delta\phi$	then	$R_\phi=1$
	$-\Delta\phi \le e_\phi < 0$	then	$R_\phi=2$
	$e_\phi < -\Delta\phi$	then	$R_\phi=3$

The predefined error level of the torque controller is divided into two parts and the table 3 gives the switching sequences. Figure 6 shows the performance analysis of the proposed non hysteresis controller scheme.

	R_C	0	1	2	3	4
		N				
R_ϕ	0	Z+1	Z	Z	0	Z-1
	1	Z+1	Z+1	0	0	Z-1
	2	Z+2	Z+2	0	0	Z-2
	3	Z+2	Z+3	Z+3	0	Z-2

N	0	1	2	3	4	5	6	7
S	V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7

Table 3. Switching sequences of the control.

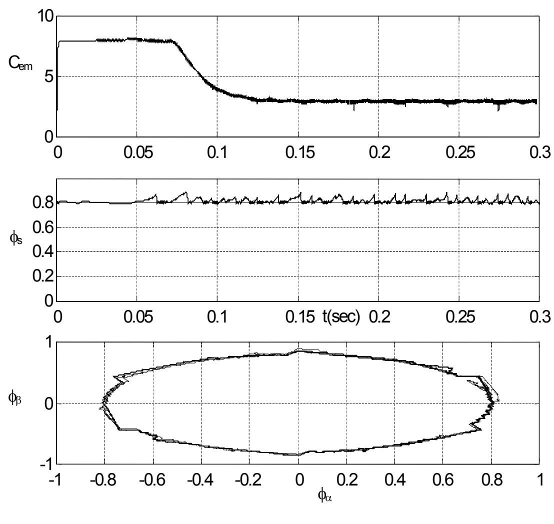

Figure 6. Performance of the non-hysteresis controllers.

The flux controller tries to keep the lower and upper boundaries of the flux. This technique can be classified based on the number of the error levels and has advantages of,

- Lower switching frequency.
- Less memory required comparatively with the previous techniques.
- Reduced programming efforts.

5. Modified Control with Injection of Dither Signal.

A modified DTC method introduces a dither signal by superposing a high frequency and small amplitude triangular or sine wave on the torque and flux errors. According to the several simulation results illustrated in figure 7, the stator flux and torque ripples were reduced compared to those of conventional scheme and this enables the controller to raise the switching frequency regardless of the delay time and also makes acoustically silent drive possible.

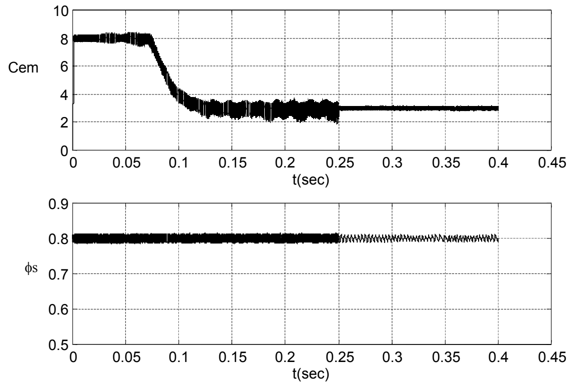

Figure 7. Performance of the proposed DTC scheme.

6. Effect of the stator resistance variation

The stator resistance Rs varies mainly due to the change of temperature which, in turn depend on such factors as duty cycle, load, ambient conditions, and speed. Some of these factors are unpredictable. There is also some change due to skin effect which depends on input frequency. The effect of the variation of stator resistance leads to large variation in estimated stator flux linkage. In DTC, the stator flux is estimated using equation (10), when φs, Vs and is represent the stator flux linkage, voltage and current vectors respectively.

$$\phi_s = \int (V_s - R_s.I_s)dt \qquad (10)$$

The variation of Rs may introduce significant errors in the calculation of stator flux and thereby the overall performance of the DTC system. At low speed, the back electromotive force term is small and the resistive drop is comparable with the supply voltage magnitude. Any change in stator resistance gives erroneous estimation of stator flux and consequently of the electromagnetic torque.

An error in the angular position of the stator flux linkage position is also important as it can cause the controller to select a wrong switching state. Simulation studies show that the drive system become unstable if the stator resistance value used in the controller is higher than that of the machine actual resistance.

Figure 8 shows that the stator flux linkage exhibits undesired oscillation when Rs is increased. So a mismatch between nominal and actual resistance value can create instability. At high speeds, the stator resistance drop is small compared to the back emf and hence can be neglected [15][17].

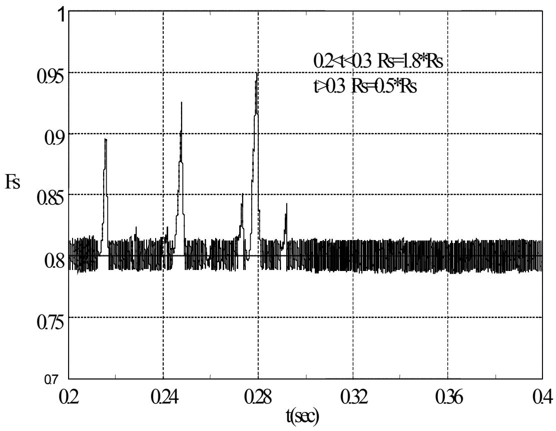

Figure 8. Effect of stator resistance variation.

The stator resistance changes due to temperature variations with a large extend and to stator frequency variation with a smaller degree. Such changes deteriorate the drive performance by introducing errors in the estimated magnitude and position of the flux linkage vector. This in turn affects the estimation of the torque, particularly at low speeds [16][17].

In reality, the stator resistance does not change in step manner. So, the instability result under a step change is not so practical. In actual operating conditions, the rate of change of temperature is very slow and so the stator resistance changes in an unpredictable manner.

7. Effect of the offsets in measurement

The source of offset in measurement is the thermal offset of analog integrators used in signal processing. Offset also arises from DC components which result after a transient change. In reality, the offset is unpredictable and changes with temperature. It may introduce unacceptable drift in the stator flux estimation and then causes an error in torque estimation, so the drive system may become unstable. The offset error is non periodical and unidirectional. They are examined by extensive simulation studies. Figure 9 shows the modelling results when offset error is artificially introduced in direct current component. It is seen that the accumulation of the offset error in current causes the torque oscillation to increase and the stator to drift from its origin. The compensation for this drift is possible with programmable cascaded low pass filter.

$$\phi_{\alpha.actual} = \phi_\alpha - \tfrac{\sqrt{3}}{2}.R_s.\int I_a.dt \quad (11)$$

$$\phi_{\beta.actual} = \phi_\beta - \tfrac{1}{\sqrt{2}}.R_s.\int (I_b - I_c).dt \quad (12)$$

Offsets in measurement of the DC-link voltage and phase currents are inevitable. They are due to the sensors and the signal conditioning circuits used. The centred circle shows the stator flux linkage when the actual DC link voltage is the nominal value. The inner circle in figure 10 indicates the flux linkage when E= 0.9*En and the larger circle represents Φs when E=1.2*En.

$$V_s = \sqrt{\tfrac{2}{3}}.(E + \Delta E).(S_{h1} + a.S_{h2} + a^2.S_{h3}) \quad (13)$$

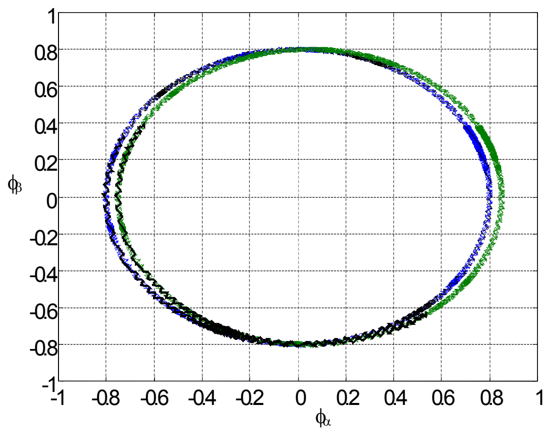

Figure 9. Effect of the offset in current measurement

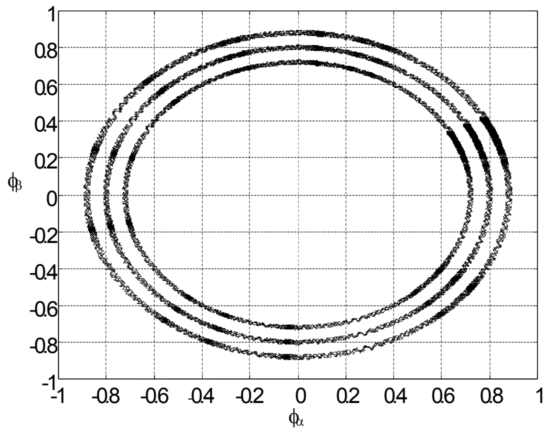

Figure 10. Effect of the offset in DC voltage measurement

8. Conclusion.

The use of switching table with zero voltage vectors revealed loss of control, which could not attributed to factors such offsets in measurement and variation of stator resistance which are known sources of problems for the DTC.

The eight voltage vectors switching table is found to be preferable for high speed operating conditions with lower torque and stator flux ripples. The main advantages of the combined structure are,

- Stable and efficient structure.
- Improvement of torque ripple characteristic in a large speed range.
- Fast response and robustness merits entirely preserved.

The results indicate that the non-hysteresis controllers are cheaper and consume less electric power than the hysteresis controllers. The non-hysteresis controllers and modified DTC with dither signal have some important advantages as compared to the basic DTC algorithm such as, low switching frequency with identical sampling frequencies. Also, the logic of the modified controller is simpler and more suitable for on-line applications. Consequently, the reduced switching pattern leads to a lower primary and operational cost of the inverter.

It is seen that the DTC algorithm is capable of working from low speed to high speed and exhibits very good dynamic and steady state performance. However, the offset error may deteriorate the performance by introducing error in the estimated flux linkage and in turn causes the torque of a motor to oscillate at the stator electrical frequency.

APPENDIX
RATED DATA OF THE SIMULATED PMSM

Rated values			
	Frequency	50 Hz	
	Voltage (Δ/Y)	220 V	
	Speed	1500 rpm	
	Torque	3 N·m	
	Pole pair (n_p)	2	
Rated parameters			
	ϕf	0.314	Wb
	L_d	0.0349	H
	L_q	0.0627	H
	J	0.003	kg·m^2
	f	0.00008	N·m·s
	Rs	*1.4 Ω*	

References

[1] T.M. Jahns, "motion control with PM machines," *Proc.of the IEEE*, vol. 82, n°8, pp.1241-1252; 1994..

[2] L. Zhong,M.F.Rahman, W.Y.Hu, "Analysis of direct torque controlin PMSM drives," *IEEE Trans. Power Electronics*, vol. 12, n°3, pp. 528-536, 1997.

[3] M.N. Uddin and al., "Performance of current controllers for IPMSM drive," *in Proc. of the IEEE IAS Annual Meeting*, vol. 2, pp. 1018–1025, 1999.

[4] M. Kadjoudj, R.Abdessemed, M.E. Benbouzid, C. Ghennai, "Current control of PMSM fed by two and three levels VSI," *in Proc. of EPE/PEMC*, Tuke (Slovakia), vol. 7, pp. 69-74, 2000.

[5] J.K.Kang,S.K.Sul, "New direct torque control of induction motor for minimum torque ripple and constant switching frequency," *IEEE Trans. On ind. Appl.*, vol. 35, n°5, pp. 1076-1082,1999.

[6] S.K. Chung and al., "A new instantaneous torque control of PMSM for high performance direct drive applications," *IEEE Trans. Power Electronics*, vol. 13, n°3, pp. 388-400, 1998.

[7] K.M. Rahman, "Variable Band hysteresis current controllers for PWM VSI," *IEEE Trans. Power Electronics*, vol. 12, n°6, pp. 964-970, 1997.

[8] C. French, P. Acarnley, "Direct torque control of permanent magnet drives," *IEEE Trans. On ind. Appl.*, vol. 32, n°5, pp. 1080-1088. 1996.

[9] C. Lascu, I. Boldea,F.Blabjerg, "A modified Direct torque control for induction motor sensorless drive," *IEEE Trans. On ind. Appl.*, vol. 36, n°1, pp. 22-30, 2000.

[10] J.K.Kang. D. Chang, S.K.Sul , "DTC of induction machine with variable amplitude control of flux and torque hysteresis bands," conf. of the *IEEE*, vol. 1, pp. 640-642, 1999.

[11] M. Kadjoudj, M.E. Benbouzid, C. Ghennai, D.Diallo, "A Robust hybrid current control for PMSM drives," IEEE trans. on energy conversion, vol. 19 No 1. pp. 109-115, 2004.

[12] M. Kadjoudj, N:Golea, M. Benbouzid, "Problems of stator flux estimation in DTC of PMSM drives," MS'06 conference 27-30 August Konya Turkey, Vol. 1, pp. 55-60, 2006.

[13] J.Faiz, H.M.Zonoozi, "A Novel technique and control of stator flux of a salient pole PMSM in DTC method based on MTPF," IEEE trans. on industrial electronics, vol. 50 No 2. pp. 262-271, April 2003.

[14] J.Luukko, O.Pyrhonen, M.Niemela, J.Pyrhonen "Limitation of the load angle in a direct torque controlled synchronous machine drive," IEEE trans. on industrial electronics, vol. 51 No 4. pp. 793-798, August 2004.

[15] A.Llor, B.Allard, X.Lin-Shi, J.M.Rtif, "Comparison of DTC implementations for synchronous machines," 35th annual IEEE power electronics conference, Aachen Germany, pp. 3581-3587, 2004.

[16] L.Tang, L.Zhong, M.Rahman and Y.Hu, "A Novel direct synchronous machine drive with fixed switching frequency," IEEE trans. on power electronics, vol. 19 No 2. pp. 262-271, Marsh 2004.

[17] M.F.Rahman, M.E.Haque, L.Tang, L.Zhong, "Problems associated with the DTC of an interior PMSM drive and their remedies," IEEE trans. on industrial electronics, vol. 51 No 4. pp. 799-808, August 2004.